Fission-Energy Release for 16 Fissioning Nuclides

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PROJECT DESCRIPTION

One of the most important basic parameters required for nuclear reactor design and safety analysis is the amount of energy released in a fission event. Knowledge of this quantity and its distribution among the various components resulting from a fission event is required for the determination of the power level of a reactor during normal operation and the decay heat generation during transients.

The energy release in fission can be determined by comparing the masses of fission products to the original mass of the fissioning nucleus or by adding the measured fission fragment and fission decay energies.

PROJECT OBJECTIVE

The objective of this work was to conduct a systematic study of the energy releases in fission and the components of this energy (kinetic energy of fission fragments, prompt neutrons, prompt gamma rays, beta rays, neutrinos, delayed gamma rays, and neutrons).

PROJECT RESULTS

Energy releases for 16 fissioning nuclei have been determined. For "primary" isotopes (for which relatively good experimental quantities exist), this determination was made by a combination of mass-defect systematics and least-square fits with the experimental data. For remaining isotopes only the systematic study was carried out. The fission energies determined in this study have been included in the National Reference Nuclear Data Library ENDF/B Version 5.

This report was primarily intended as a reference for nuclear data development projects. It should also be of interest to utility engineers responsible for fuel-cycle optimization and safety analysis.

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ABSTRACT

Results are presented of a least-squares evaluation of the components of energy release per fission in Th-232, U-233, U-235, U-238, Pu-239, and Pu-241. For completeness, older (1978) results based on systematics are presented for these and ten other isotopes of interest. There have been recent indications that the delayed energy components may be somewhat higher than those used previously, but the LSQ results do not seem to change significantly when modest (~ 1 MeV) increases in the total delayed energy are included in the inputs. Additional measurements of most of the energy components are still needed to resolve remaining discrepancies.

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SUMMARY

For calculations of heat balance and decay heat in reactors, it is important to know the energy release per fission and its various components: fragment kinetic energies and prompt and delayed radiation. The total energy per fission can be determined either by mass balance after fission product decay or by adding the individual components. With improved fission yield and mass-defect data, the mass balance equation can give the total energy release to within 0.25 MeV or better for the "primary" fissionable isotopes: ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. For other fissionable isotopes, the uncertainties in the mass balance method may be as high as one percent (~ 2 MeV).

Experimental and calculated data on the individual components are somewhat sparse and are not as accurate as the mass balance data. In this work, such data are combined with mass balance results and improved systematics in a least-squares evaluation to obtain best values for the total and component energies for the six primary isotopes. For other fissionable isotopes, the improved systematics are employed.

Section I

INTRODUCTION

The energy release in fission and its partition into fragment kinetic energy and radioactive decay energy are important for determining reactor power and in safety considerations, which depend on the decay heat. The energy release can be determined in two ways: by mass balance after fission product decay, and by adding the individual components of the fragment and decay energies. The first of these methods has been exploited by Walker [1-3], Unik and Gindler [4], and James [5,6]. With increasing knowledge of fission fragment yields [7,8] and mass defects [9], it is possible to calculate total energy releases from mass balance to within approximately ±0.1 MeV for neutron-induced fission of U-233 and U-235, ±0.2 MeV for U-238, Pu-239, and Pu-241, and ±0.3MeV for Th-232, and to somewhat poorer accuracy for other isotopes.

The individual components of the energy release (kinetic energy of the fragments and prompt neutrons, prompt gamma rays, beta rays, neutrinos, and delayed gamma rays and neutrons) were determined from a combination of experimental values and nuclear systematics, in general, these were much less precise and did not always correctly add up to the total energy release.

In this report we continue to utilize these methods, analyzing 16 fissioning isotopes in all. For the isotopes listed above ("primary" isotopes), for which relatively good values of yields and other experimental quantities exist, best values of the total and partial energies are determined by a combination of systematics and a least-squares calculation. Systematics are used for the other isotopes. The systematics are checked against the least-squares values for the primary isotopes, agreement between the two methods is always good (~ ±1 MeV).

It is convenient at this point to define various quantities of interest:

QG = the net energy release per fission. This includes the antineutrino energy, but does <u>not</u> include subsequent radiative capture of the fission neutrons in a reactor. Otherwise it is the total energy released minus the incident neutron energy.

ED = the total (delayed) radioactive decay energy per fission. It is the sum of the beta-ray, delayed gamma ray, and antineutrino energies of all the decay products of the fission fragments (delayed neutrons not included).

EB = beta-ray decay energy per fission.

EGD = delayed gamma-ray decay energy per fission.

ENU = antineutrino decay energy per fission.

ER = "effective" energy release per fission, ER = QG - ENU + EINC.

EP = the total prompt energy release per fission; it is the sum of the kinetic energies of the fragments and fission neutrons, and the prompt ($\lesssim$ 10 nsec) gamma-ray energy, minus the incident neutron energy.

EFR = fragment kinetic energy per fission (post-neutron emission).

EGP = prompt gamma-ray energy per fission.

ENP = average prompt neutron energy per fission.

EINC = average incident neutron energy (= 0 for thermal fission).

END = average delayed neutron energy per fission.

ET = the conventionally defined Q-value of the fission reaction, ET = QG + EINC.

All of the above quantities are averages over all modes of fission and are determined for a given fissionable nuclide and incident neutron energy. For fast-fissioning isotopes, EINC is taken to be the average energy of a U-235 fission neutron, weighted by the fission density of the isotope, i.e.,

$$\mathrm{EINC}^{(i)} = \frac{\int E f_{25}(E)\ \sigma_{fi}(E)\ dE}{\int f_{25}(E)\ \sigma_{fi}(E)\ dE} \qquad (1)$$

where $f_{25}(E)$ is the U-235 fission spectrum and the index i refers to the fissionable nuclide. Typically, the value of EINC for fast fission when averaged according to Eq. (1) is about 3 MeV. Walker [10] has examined the values of the various energy components calculated from the ENDF/B-5 yield set as a function of incident neutron energy and has proposed that, for those nuclides which fission only with fast neutrons, the components be estimated and listed in the ENDF-B library at zero neutron incident energy. He gives approximate expressions for determining the zero energy values from the values at other EINC.

However, in this paper, we continue to report values appropriate to average EINC's as defined above.

From the above definitions,

$$QG = EP + ED + END = ER + ENU - EINC \quad (2)$$

$$EP = EFR + EGP + ENP - EINC \quad (3)$$

$$ED = EB + EGD + ENU \quad (4)$$

Walker [3] has pointed out that the Q-value, ET (= QG + EINC), for a given fissionable isotope is almost independent of EINC. Since the biggest change in QG is due to an increase in ν_t, this can be interpreted as meaning that most of the incident neutron energy is simply used to produce extra neutrons. It should be noted that ternary fission is neglected in what follows.

Section II

TOTAL ENERGY RELEASE, QG

From the chain yields, QG can be obtained from the mass-balance equation:

$$QG = - \langle M_\ell \rangle - \langle M_h \rangle + M(Z_0,A_0) - (\overline{\nu}_t - 1)\, m_n \qquad (5)$$

Here $\langle M_\ell \rangle$ is the average mass excess of the final decay products of the light fragments:

$$\langle M_\ell \rangle = \sum_i^{(light)} Y_i M_i \quad . \qquad (6)$$

$\langle M_h \rangle$ is the average mass excess of the end products of the heavy fragments, Y_i are the chain yields, M_i is the mass excess of the end product i, $M(Z_0,A_0)$ is the mass excess of the target nucleus (Z_0,A_0), and m_n is the mass excess of the neutron (= 8.07144 MeV).

Beck [11] carefully reviewed the yield and mass data and recalculated QG values, these values are shown in Table I. In obtaining these values, the yield sets of Meek and Rider [7] and Crouch [8] were used with mass data [9] for 12 of the 17 nuclides shown. For Pa-233, U-234, Pu-238, Am-243, and Cm-244, systematics were used to determine the mass defects.

Table I

QG by Mass Balance--Recommended Values[a]

Nuclide	QG (MeV)
Th-232	195.93 ± 0.32
Pa-233	196.62 ± 0.66
U-233	198.02 ± 0.10
U-234	197.78 ± 0.65
U-235	202.53 ± 0.10
U-236	201.82 ± 0.12
U-238	206.01 ± 0.17
Np-237	202.23 ± 0.80
Pu-238	204.66 ± 0.24
Pu-239	207.02 ± 0.14
Pu-240	205.66 ± 0.23
Pu-241	210.73 ± 0.23
Pu-242	209.47 ± 0.82
Am-241	209.51 ± 0.24
Am-243	209.80 ± 0.88
Cm-244	211.52 ± 0.87
Cf-252	217.66 ± 0.11

[a]Ref. 9.

Section III

PROMPT ENERGY RELEASE, EP

The quantity EP = QG - ED - END is the prompt energy release. It is equal to the sum of the kinetic energy of the fragments, the kinetic energy of the (prompt) neutrons (minus the mean incident neutron energy), and the prompt gamma-ray energy. It can also be independently determined from the individual fragment direct yields:

$$EP = M(A_0,Z_0) - \langle m_\ell \rangle - \langle m_h \rangle - (\bar{\nu}_p - 1)\, m_n \quad . \qquad (7)$$

Here, $\langle m_{\ell,h} \rangle = \sum y_i m_i^{\ell,h}$, where y_i is the independent (direct) yield of a fragment, m_i is its mass excess, and $\bar{\nu}_p$ is the average number of prompt neutrons emitted per fission.

Values of EP have been recalculated [11] with the independent yield set of Walker [12], based on Meek and Rider [13]. Since this yield set (and also more recent ones) does not conserve total yields along Z (that is, the sum of the direct yields of fragments with atomic number Z does not in general equal the sum of fragment yields with complementary charge Z' (= Z_A-Z, where Z_A is the atomic number of the fissioning nuclide), the sensitivity of EP to adjustments in the yield sets was investigated. It was found that, although some chain yields changed under the adjustment by substantial amounts, EP calculated from any of the yield sets varied by less than 0.1%. Table II lists the values of EP.

Table II

Prompt Energy Release, EP[a]

Nuclide	EINC (MeV)	EP (MeV)
Th-232	3.35	168.73
U-233	thermal	180.76
U-235	thermal	180.76
U-238	3.10	178.24
Pu-239	thermal	189.52
Pu-241	thermal	189.15

[a]Ref. 11.

Section IV

DECAY ENERGY, ED

For the primary isotopes, ED has been calculated by Walker from the direct fission product yields and their known decay properties, in addition, more accurate results have been obtained by him from long-term irradiation calculations using FISSPROD [12]. A striking characteristic of these results is that the fractions of ED that respectively represent beta energy (EB), gamma energy (EGD), and antineutrino energy (ENU) are nearly constant for all the primary isotopes (see Table III), that is,

$$\frac{EB}{ED} = .3015 \pm .0010 \quad ,$$

$$\frac{EGD}{ED} = .2932 \pm .0015 \quad ,$$

$$\frac{ENU}{ED} = .4053 \pm .0015 \quad .$$

We assume that this split of ED holds for all fissioning isotopes of interest. Recently, Walker [3] has slightly revised his values of ED, the new values are shown in Table IV. For other isotopes, ED was obtained from systematics [11].

Table III

Fission Product Decay Energy Partition[a]

Isotope	Total Decay Energy	Beta Energy		Gamma Energy		Neutrino Energy	
	ED (MeV)	EB (MeV)	EB/ED	EGD (MeV)	EGD/ED	ENU (MeV)	ENU/ED
Th-232	27.25	8.27	.304	8.02	.294	10.95	.402
U-233	17.02	5.09	.299	5.07	.298	6.86	.403
U-235	21.37	6.44	.301	6.28	.294	8.65	.405
U-238	27.46	8.31	.303	8.07	.294	11.08	.403
Pu-239	17.28	5.17	.299	5.04	.292	7.07	.409
Pu-241	21.49	6.51	.303	6.17	.287	8.82	.410
Average			.3015 ±.0010		.2932 ±.0015		.4053 ±.0015

[a]Ref. 12.

Table IV

Decay Energies, ED[a]

Nuclide	EINC (MeV)	ED (MeV)
Th-232	3.35	26.82
U-233	thermal	16.84
U-235	thermal	21.26
U-236	2.82	22.95
U-238	3.10	27.24
Np-237	2.37	18.36
Pu-239	thermal	17.49
Pu-240	2.39	19.04
Pu-241	thermal	21.70
Pu-242	2.32	21.96
Cf-252	(spontaneous)	19.99

[a]Ref. 3.

Section V

LEAST-SQUARES CALCULATIONS OF ENERGY RELEASE

The data given in Tables I, II, and IV can be combined with experimental data on EFR and EGP in a least-squares calculation to get "best" values of all the energy-release parameters. We use the following "observational equations" for the primary isotopes (Th-232, U-233, U-235, U-238, Pu-239, and Pu-241):

$$ED + EGP + EFR = QG - (ENP-EINC) - END \qquad (8)$$

The quantities on the l.h.s. are assumed to be unknown, those on the r.h.s. are assumed to be known (QG is taken from Table I).

$$EFR + EGP = EP - (ENP-EINC) \ . \qquad (9)$$

Again, the quantities on the r.h.s. are assumed known (EP from Table II) and independent of those in the preceding equation.

In addition to these types of observational equations, in which the "experimental" values are those on their right-hand sides, direct measurements of EFR, EGP, ratios of EFR between different isotopes, and a few calculated values of ratios of EDs based on systematics are also used as inputs to the LSQ calculation.

Table V lists all the foregoing data, together with the weight factors assigned to each observational equation. It should be noted that the weight factors are proportional to the inverse squares of the absolute errors of each experimental value. The error values are either as quoted by the author or are estimates made by us. The LSQ calculations then give the best values of EFR, ED, and EGP shown in Table VI. From the ratios given in Table III, EB, EGD, and ENU are then obtained. By summing the appropriate quantities, values of QG and EP are obtained, but these are not as good as the input values obtained from yield data, which are therefore recommended, as indicated in Table VI.

Table V

LSQ Input Data and Observational Equations

Input Data	Weight	Observational Equation
Th-232:		
$EFR^{232} = 159.80 \pm 2.0$	0.25	$0.25\ x_1 = 39.95$
$EFR^{232} + ED^{232} + EGP^{232} = QG^{232} - (ENP^{232} - EINC^{232}) - END^{232}$		
$= 194.56 \pm 0.26$	15	$15x_1 + 15x_2 + 15x_3 = 2918.4$
$EFR^{232} + EGP^{232} = EP^{232} - (ENP^{232} - EINC^{232})$		
$= 167.38 \pm 0.30$	10	$10x_1 + 10x_3 = 1673.8$
$ED^{232} = 26.82 \pm 0.27$	4[a]	$4x_2 = 107.28$
$ED^{232}/ED^{235} = 1.19 \pm 0.06$	0.6	$0.6x_2 - 0.714x_8 = 0$
$(ED^{232} - 1.19\ ED^{235} = 0 \pm 0.06\ ED^{235})$		
$EGP^{232} = 6.96 \pm 1.0$	1	$x_3 = 6.96$
U-233:		
$EFR^{233} = 167.36 \pm 2$	0.25	$0.25x_4 = 41.84$
$EFR^{233} + ED^{233} + EGP^{233} = QG^{233} - ENP^{233} - END^{233}$		
$= 193.12 \pm 0.2$	25	$25x_4 + 25x_5 + 25x_6 = 4828$
$EFR^{233} + EGP^{233} = EP^{233} - ENP^{233}$		
$= 175.85 \pm 0.25$	16	$16x_4 + 16x_6 = 2813.76$
$EFR^{233}/EFR^{238} = 0.9916 \pm 0.0015$	18	$18x_4 - 17.8488x_{10} = 0$
$EFR^{233}/EFR^{235} = 0.9953 \pm 0.0025$	5.7	$5.7x_4 - 5.6732x_7 = 0$
$ED^{233} = 16.84 \pm 0.12$	10[a]	$10x_5 = 168.4$
$ED^{233}/ED^{235} = 0.81 \pm 0.04$	1.4	$1.4x_5 - 1.134x_8 = 0$
$EGP = 6.96 \pm 1.0$	1	$x_6 = 6.96$

[a]Reduced weight, see text.

Table V (cont.)

Input Data	Weight	Observational Equation
U-235:		
$EFR^{235} = 167.93 \pm 2.0$	0.25	$0.25x_7 = 41.9825$
$EFR^{235} + ED^{235} + EGP^{235} = QG^{235} - ENP^{235} - END^{235}$		
$= 197.73 \pm 0.12$	70	$70x_7 + 70x_8 + 70x_9 = 12841$
$EFR^{235} + EGP^{235} = EP^{235} - END^{235}$		
$= 175.97 \pm 0.20$	25	$25x_7 + 25x_9 = 4399.25$
$ED^{235} = 21.26 \pm 0.15$	10[a]	$10x_8 = 212.6$
$ED^{235} = 23.8 \pm 1.6$	0.4	$0.4x_8 = 9.52$
$ED^{235} = 22.18 \pm 1$	1	$x_8 = 22.18$
$EGP^{235} = 6.73 \pm 1.0$	1	$x_9 = 6.73$
U-238:		
$EFR^{238} = 167.93 \pm 2.0$	0.25	$0.25x_{10} = 41.9825$
$EFR^{235}/EFR^{238} = 0.9968 \pm 0.0014$	18	$18x_7 - 17.9424x_{10} = 0$
$EFR^{235}/EFR^{238} = 0.9996 \pm 0.0025$	5.7	$5.7x_7 - 5.6977x_{10} = 0$
$EFR^{238} + ED^{238} + EGP^{238} = QG^{238} - (ENP^{238} - EINC^{238}) - END^{238}$		
$= 203.58 \pm 0.32$	10	$10x_{10} + 10x_{11} + 10x_{12} = 2035.8$
$EFR^{238} + EGP^{238} = EP^{238} - (ENP^{238} - EINC^{238})$		
$= 175.83 \pm 0.4$	6	$6x_{10} + 6x_{12} = 1054.98$
$ED^{238} = 27.24 \pm 0.19$	10[a]	$10x_{11} = 272.4$
$ED^{238} = 27.2 \pm 1.0$	1	$x_{11} = 27.2$
$ED^{238}/ED^{235} = 1.265 \pm 0.06$	0.44	$0.44x_{11} - 0.5566x_8 = 0$
$EGP^{238} = 6.96 \pm 1.0$	1	$x_{12} = 6.96$

[a]Reduced weight, see text.

Table V (cont.)

Input Data	Weight	Observational Equation
<u>Pu-239:</u>		
$EFR^{239} = 175.77 \pm 0.10$	100	$100x_{13} = 17577$
$EFR^{239} + ED^{239} + EGP^{239} = QG^{239} - ENP^{239} - END^{239}$		
$= 201.12 \pm 0.2$	25	$25x_{13} + 25x_{14} + 25x_{15} = 5028$
$EFR^{239} + EGP^{239} = EP^{239} - ENP^{239}$		
$= 183.62 \pm 0.25$	16	$16x_{13} + 16x15 = 2937.92$
$ED^{239} = 17.49 \pm 0.12$	10[a]	$10x_{14} = 174.9$
$ED^{239} = 18.36 \pm 1.0$	1	$x_{14} = 18.36$
$ED^{239}/ED^{235} = 0.878 \pm 0.0044$	0.9	$0.9x_{14} - 0.7902x_8 = 0$
$EGP^{239} = 7.05 \pm 1.0$	1	$x_{15} = 7.05$
<u>Pu-241:</u>		
$EFR^{241} = 174.12 \pm 2.0$	0.25	$0.25x_{16} = 43.53$
$EFR^{241}/EFR^{235} = 1.0353 \pm 0.005$	1.4	$1.4x_{16} - 1.4494x_7 = 0$
$EFR^{241} + ED^{241} + EGP^{241} = QG^{241} - ENP^{241} - END^{241}$		
$= 204.74 \pm 0.31$	10	$10x_{16} + 10x_{17} + 10x_{18} = 2047.4$
$EFR^{241} + EGP^{241} = EP^{241} - ENP^{241}$		
$= 183.16 \pm 0.3$	10	$10x_{16} + 10x_{18} = 1831.6$
$ED^{241} = 21.7 \pm 0.15$	10[a]	$10x_{17} = 217$
$ED^{241}/ED^{235} = 1.056 \pm 0.053$	0.7	$0.7x_{17} - 0.7392x_8 = 0$
$EGP^{241} = 6.96 \pm 1$	1	$x_{18} = 6.96$

[a]Reduced weight, see text.

Table VI

Results of LSQ Calculations and Systematics for Primary Isotopes[a]

(MeV/fission)

	Th-232		U-233		U-235	
	LSQ	Systematics	LSQ	Systematics	LSQ	Systematics
QG	195.82 ± 1.3	195.93 ± 0.2	197.93 ± 0.8	198.02 ± 0.12	202.48 ± 0.72	202.53 ± 0.06
ED	26.97 ± 0.31	27.19 ± 1.5	17.10 ± 0.21	18.54 ± 1.5	21.60 ± 0.17	22.83 ± 1.00
EP	168.85 ± 0.9	168.73 ± .25	180.84 ± 0.73	180.76 ± 0.15	180.88 ± 0.70	180.76 ± 0.10
EB	8.13 ± 0.10	8.19 ± 0.5	5.16 ± 0.06	5.58 ± 0.5	6.50 ± 0.05	6.87 ± 0.30
EGD	7.91 ± 0.10	8.2 ± 0.75	5.01 ± 0.06	5.47 ± 0.75	6.33 ± 0.05	6.74 ± 0.50
ENU	10.93 ± 0.13	10.99 ± 1.1	6.93 ± 0.09	7.49 ± 1.10	8.75 ± 0.07	9.22 ± 0.80
EFR	160.39 ± 0.92	159.81 ± 2.0	168.21 ± 0.50	167.36 ± 2.0	169.12 ± 0.49	167.93 ± 2.0
EGP	7.11 ± 0.90	6.96 ± 1.0	7.73 ± 0.52	6.96 ± 1.0	6.97 ± 0.50	6.73 ± 1.0
ENP	4.7 ± 0.12	4.7 ± 0.12	4.9 ± 0.1	4.9 ± 0.1	4.79 ± 0.07	4.79 ± 0.07
EINC	3.35 ± 0.10	3.35 ± 0.1	(thermal)	(thermal)	(thermal)	(thermal)
END	0.022 ± 20%	0.022 ± 20%	0.031 ± 15%	0.0031 ± 15%	0.0074 ± 15%	0.0074 ± 15%

[a]Recommended values are underlined.

Table VI (cont.)[a]

	U-238		Pu-239		Pu-241	
	LSQ	Systematics	LSQ	Systematics	LSQ	Systematics
QG	205.87 ± 0.8	206.01 ± .26	207.06 ± 0.33	207.02 ± 0.13	210.83 ± 1.0	210.73 ± 0.22
ED	27.35 ± 0.25	28.93 ± 1.5	17.62 ± 0.21	20.05 ± 1.5	21.84 ± 0.30	24.18 ± 1.5
EP	178.52 ± 0.75	178.24 ± 0.30	189.44 ± 0.26	189.52 ± 0.15	188.99 ± 1.0	189.15 ± 0.25
EB	8.25 ± 0.08	8.71 ± 0.5	5.31 ± 0.06	6.03 ± 0.5	6.58 ± 0.09	7.28 ± 0.5
EGD	8.02 ± 0.07	8.53 ± 0.75	5.17 ± 0.06	5.91 ± 0.75	6.40 ± 0.09	7.13 ± 0.75
ENU	11.08 ± 0.10	11.69 ± 1.1	7.14 ± 0.09	8.10 ± 1.1	8.85 ± 0.12	9.77 ± 1.1
EFR	169.57 ± 0.49	167.93 ± 2.0	175.78 ± 0.1	173.85 ± 2.0	175.36 ± 0.68	174.12 ± 2.0
EGP	6.54 ± 0.53	6.96 ± 1.0	7.76 ± 0.22	7.05 ± 1.0	7.64 ± 0.69	6.96 ± 1.0
ENP	5.51 ± 0.10	5.51 ± 0.10	5.9 ± 0.1	5.9 ± 0.1	5.99 ± 0.13	5.99 ± 0.13
EINC	3.10 ± 0.10	3.10 ± 0.10	(thermal)	(thermal)	(thermal)	(thermal)
END	0.018 ± 15%	0.018 ± 15%	0.0028 ± 15%	0.0028 ± 15%	0.005 ± 20%	0.005 ± 20%

[a]Recommended values are underlined.

Section VI

SYSTEMATICS

Beck [11] has reviewed the systematics of the various quantities, and his results have been applied both to the primary isotopes (where the results are not as good as the LSQ values) and to the other isotopes of interest, for which there are insufficient data to do a LSQ calculation. For the primary isotopes, the values obtained by systematics are also listed in Table VI; for the others they are given in Table VII. For a detailed discussion of the systematics, Beck [11] should be consulted.

Table VII

Results of Systematics for Other Isotopes[a]

(MeV/fission)

	Pa-233	U-234	U-236	Np-237	Pu-238
QG	196.62 ± 0.66	197.78 ± 0.65	201.82 ± .12	202.23 ± .80	204.66 ± 0.24
ED	23.29 ± 1.5	20.16 ± 1.5	24.43 ± 1.5	20.69 ± 1.5	18.01 ± 1.5
EP	175.75 ± 2.32	179.41 ± 2.31	179.89 ± 2.26	183.69 ± 2.35	186.46 ± 2.26
EB	7.01 ± 0.5	6.07 ± 0.5	7.35 ± 0.5	6.23 ± 0.5	5.42 ± 0.5
EGD	6.87 ± 0.75	5.95 ± 0.75	7.21 ± 0.75	6.10 ± 0.75	5.31 ± 0.75
ENU	9.41 ± 1.10	8.14 ± 1.10	9.87 ± 1.10	8.36 ± 1.10	7.28 ± 1.10
EFR	163.5 ± 2.0	167.1 ± 2.0	167.5 ± 2.0	170.6 ± 2.0	173.6 ± 2.0
EGP	6.96 ± 1.0	6.96 ± 1.0	6.96 ± 1.0	6.96 ± 1.0	6.96 ± 1.0
ENP	5.28 ± 0.42	5.36 ± 0.43	5.41 ± 0.29	6.17 ± 0.48	5.92 ± 0.34
EINC	3.0 ± 0.3	2.36 ± 0.10	2.82 ± 0.10	2.37 ± 0.10	(thermal)
END	0.01 ± 25%	0.005 ± 20%	0.01 ± 20%	0.005 ± 25%	0.002 ± 20%

[a]Ref. 11.

Table VII (cont.)

Results of Systematics for Other Isotopes[a]

(MeV/fission)

	Pu-240	Pu-242	Am-241	Am-243	Cm-244
QG	205.66 ± 0.23	209.47 ± 0.82	209.51 ± 0.24	209.80 ± 0.88	211.52 ± 0.87
ED	21.39 ± 1.5	25.60 ± 1.5	18.68 ± 1.5	21.81 ± 1.5	21.03 ± 1.5
EP	187.43 ± 2.27	187.94 ± 2.34	189.82 ± 2.27	191.03 ± 2.37	193.08 ± 2.29
EB	6.44 ± 0.5	7.70 ± 0.5	5.62 ± 0.5	6.56 ± 0.5	6.33 ± 0.5
EGD	6.31 ± 0.75	7.55 ± 0.75	5.51 ± 0.75	6.43 ± 0.75	6.20 ± 0.75
ENU	8.64 ± 1.10	10.34 ± 1.10	7.54 ± 1.10	8.81 ± 1.10	8.50 ± 1.10
EFR	173.7 ± 2.0	174.0 ± 2.0	176.4 ± 2.0	176.3 ± 2.0	178.5 ± 2.0
EGP	6.96 ± 1.0	6.96 ± 1.0	6.96 ± 1.0	6.96 ± 1.0	6.96 ± 1.0
ENP	6.77 ± 0.36	6.98 ± 0.54	6.53 ± 0.36	7.77 ± 0.59	7.62 ± 0.58
EINC	2.39 ± 0.10	2.32 ± 0.10	(thermal)	3.0 ± 0.5	(thermal)
END	0.004 ± 20%	0.010 ± 20%			

[a]Ref. 11.

Section VII

DELAYED NEUTRON CONTRIBUTION, END

It should be noted that the values of END shown in Tables VI and VII are obtained by multiplying the delayed neutron yield per fission [14] by the average energy per delayed neutron. For the primary isotopes, the average energy per delayed neutron was computed from the delayed neutron spectra evaluated by Saphier et al. [15]. These averages are shown in Table VIII, together with the values of ν_d used and the resulting END.

For all other nuclides, the average energy per delayed neutron was taken as 0.455 MeV. The values of ν_d are taken from Tuttle [14], except for Pa-233, Np-237, Am-243, and Cm-244, for which they are assumed to be 0.02, and Am-241, for which it is assumed to be 0.01. These values should only be considered as "ballpark" guesses.

Table VIII

Average Energy Per Delayed Neutron

Nuclide	Average Energy/ Del. Neutron (MeV)[a]	$\bar{\nu}_d$ [b]	E_d (MeV)c
Th-232	0.438	~ 0.05	0.022 ± 20%
U-233	0.443	0.007	0.0031 ± 15%
U-235	0.464	0.016	0.0074 ± 15%
U-238	0.460	0.04	0.018 ± 15%
Pu-239	0.463	0.006	0.0028 ± 15%
Pu-241	0.463	0.01	0.005 ± 20%

[a]Ref. 15.

[b]Ref. 14

Section VIII

DISCUSSION

The recommended results shown in Table VI form a consistent set. However, problems remain in the experimental values of some of the components, especially the fragment kinetic energies, the decay energies (beta and delayed gamma), and the prompt gamma energies. (It has been tacitly assumed that neutron energies are well determined.)

Fragment Energies

Direct measurements of fragment energies have been generally performed in two ways--by time of flight, in which the velocities of both fragments are measured (double velocity method), and by surface barrier detection of the energy spectrum of the fragments (double energy method). The double velocity results in general are lower by a few MeV than the double energy values. It is usually surmised that the double velocity results may be slightly low because of small angle scattering effects and the double energy results are slightly high by about the same amount because of charge effects on the energy calibration of the semiconductor detectors. Table IX summarizes the experimental data. For all isotopes except Pu-239, the input values for the least-squares fit was basically a simple average of all the experimental values. For Pu-239, Deruytter's [16] value was used. Recent measurements at Geel [17] (incident neutron energies in the low-lying resolved resonances of Pu-239) are in excellent agreement with Deruytter's value. However, Deruytter's and the Geel experiments were double-energy, so the nagging problem of the detector calibration may still remain. Good ($\pm$ 0.1 MeV) measurements for all isotopes using both velocity and energy methods are still required, both to resolve the existing discrepancies and to reduce the uncertainties in the final results.

Decay Energies

There are no direct measurements of total (beta and delayed gamma) decay energy. Recent scintillation and calorimetric measurements of decay energy or power at various times following irradiations of various durations suggest that the total decay energy may be slightly higher than the values calculated from the

Table IX

Summary of Pre-Neutron Emission Fragment Kinetic Energy Data[a]

U-233	U-235	Pu-239	Pu-241	Cf-252	Method	Reference
167.02±1.70	167.68±1.70	174.41±1.70			DV	Milton (1963)
				182.10±1.70	DV	Fraser (1963)
				185.40±2.00	DV	Milton (1963)
				185.70±1.90	DV	Whetstone (1963)
	167.45±1.70				DV(+DE)	Andritsopoulos (1967)
				184.90±2.00	DV	Barashkov (1971)
167.02	167.56	174.41		184.52	Average	of DV Measurements
169.02±2.0		176.22±0.50	176.12±0.50	Rel. to U-235 = 172.25[b]		Vorob'eva (1974)
	171.90±1.40			186.50±1.20	DE	Schmitt (1966)
		177.70±1.80	179.60±1.80		DE	Neiler (1966)
171.20±2.00	172.00±2.00	179.30±2.00		184.30±2.00	DE	Bennett (1967)
172.00±1.80					DE	Pleasonton (1968)
172.10±1.80	172.00±1.80	177.10±2.00		185.80±2.00	DE	Reisdorf (1971)
		175.20±1.50			DE	Toraskar (1974)
		177.95±0.04			DE	Deruytter (1974)
			179.62±2.00		DE	Hipp (1974)
171.77	171.97	177.45	179.61	184.45	Average	of DE Measurements

[a]Ref. 11.

Table IX (cont.)

Th-232	Pa-231	U-238	Np-237	Pu-240	Pu-242	Cm-245	Meth.	Reference
	166.80±2.0	170.10±2.0	174.00±2.0				DE	Bennett (1967)
163.26±2.0							DE	Sergachev (1968)
169.80±2.0							DE	Holubarsch (1971)
						180.20±0.5	DE	Unik (1974)
		170.01±2.0[b]		175.62±2.0[b]	176.02±2.0[b]			Vorob'eva (1974)
		170.82±2.0[c,d]						Okolovich (1963)

[b]Measurement relative to $\overline{E}_k$(U-235) = 172.25, renormalized to $\overline{E}_k$(U-235) = 169.76.

[c]Error estimated.

[d]Relative measurement, ratio $\overline{E}_k$(U-235)/$\overline{E}_k$(U-238) = 0.9938 reported, renormalized to $\overline{E}_k$(U-235) = 169.76

ENDF/B-4 yields. However, the data at short times are difficult to obtain and are incomplete, and the measurements do not directly determine the quantity of interest here. These measurements form the basis of the ANS decay heat standard, and have been taken into account in the least-squares fit by using values calculated from the parameters of the fitted standard function ($F(0,\infty)$, the decay energy at zero time following an infinite irradiation) [18]. Because the decay heat results indicate that some of the ENDF/B-4 data used in the calculated values of ED may be suspect, the weights assigned to the calculated values of ED in the LSQ calculation have been somewhat reduced, as indicated in Table V. Calculations were also done in which the Walker-calculated ED's were given their full weight (ignoring the ANS standard) and in which the calculated ED's were given weights of unity for Th-232, U-233, and Pu-241, zero weight for U-235, U-238, and Pu-239, with the ANS standard values for the latter isotopes given unity weights. The resulting output values with these alternatives are shown in Table X. Here also, improved experiments to determine <u>total</u> beta and gamma decay energy following a fission with accuracies of the order of ± 0.1 MeV would be useful.

Prompt Gamma Energies

Among the principal problems in measurements of the prompt gamma energy are to consistently define the time domain of "prompt" gamma-ray emission, to distinguish accurately between gamma rays emitted in fission and those which result from neutron capture or inelastic scattering at short times, and the possibility of anisotropic gamma emission [19-21]. The so-called "prompt-prompt" gamma energy (not involving isomeric decay) has been measured to ~ ± 0.3 MeV for U-233, U-235, Pu-239, and Cf-252 (see Table XI), but because of the effects mentioned above, the total uncertainty has been taken as ~ ± 0.5-1 MeV. It should be noted that the average value for the prompt gamma decay energy of these four isotopes, 6.96 ± 1 MeV, has been used for all other isotopes.

Because of the foregoing experimental uncertainties, the LSQ results are dominated by the QG and EP values determined from yield and decay data. Improved experimental data as suggested above would add independent inputs directly on the quantities of interest of the same quality and weight as the yield data and would give increased confidence in the LSQ results, they would also lead to substantial improvements in the systematics used for the other fissioning isotopes.

Finally, it would obviously be desirable to have as many measurements of energy components as possible done as a function of incident neutron energy up to ~ 20 MeV.

Table X

Effects of Different Weight Factors for ED

	Weight Factors		LSQ Output Values		
	Walker	Decay Heat Standard	EFR	ED	EGP
Th-232	14	--	160.43	26.89	7.12
	4	--	160.39	26.97	7.11
	1	--	160.36	27.04	7.10
U-233	70	--	168.28	16.91	7.77
	10	--	168.21	17.10	7.73
	1	--	168.08	17.31	7.73
U-235	44	0	169.19	21.41	7.03
	10	1	169.12	21.60	6.97
	0	1	168.99	21.78	6.97
U-238	28	0	169.64	27.29	6.51
	10	1	169.57	27.35	6.54
	0	1	169.43	27.58	6.53
Pu-239	70	0	175.78	17.51	7.82
	10	1	175.78	17.62	7.76
	0	1	175.78	17.73	7.69
Pu-241	44	--	175.42	21.73	7.64
	10	--	175.36	21.84	7.64
	1	--	175.15	22.55	7.50

Table XI

Prompt Gamma Energy-Release Data and Recommended Values[a]

Previous Evaluations:

Time range (seconds)	U-235	U-235	Pu-239
0.0 - ~ 5×10^{-8}	7.54 ± 0.84[b]	7.25 ± 0.26[c]	7.96 ± 0.94[c]
~ 5×10^{-8} - 1×10^{-6}	0.43 ± 0.22[b]	0.35 ± 0.71[c]	
1×10^{-6} - 1×10^{-3}	0.04 ± 0.02[b]	0.04 ± 0.02[c]	0.05 ± 0.03[c]
	8.01 ± 0.87	7.64 ± 0.75	8.01 ± 0.94

Data on Prompt-Prompt Fraction:

Nuclide			
U-233			6.69 ± 0.30[f]
U-235	7.25 ± 0.26[d]	6.51 ± 0.30[e]	6.43 ± 0.30[f]
Pu-239		6.82 ± 0.30[e]	6.73 ± 0.35[f]
Cf-252		6.84 ± 0.30[e]	

Recommended Values:

Nuclide	Prompt-Prompt Fraction	Total Prompt Gamma[a]	
U-233	6.69 ± 0.50	6.96 ± 1.0	These used
U-235	6.47 ± 0.43	6.73 ± 1.0	for these
Pu-239	6.78 ± 0.45	7.05 ± 1.0	isotopes
Cf-252	6.84 ± 0.50	7.11 ± 1.0	
Averages	6.70 ± 0.50	6.96 ± 1.0	Used for all others

[a]Ref. 11.
[b]Ref. 5.
[c]Ref. 4.
[d]Ref. 19.
[e]Ref. 20.
[f]Ref. 21.

Section 9

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